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THE MARTIAN BOW WAVE-THEORY AND OBSERVATION

by

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Abstract—The relationship between the trajectory of Mariner 4 in its fly-by of Mars and the calculated location of a proposed Martian bow wave arising from interaction of the solar wind and the ionosphere has been refined by inclusion of aberration effects of the planet's motion about the Sun. The modified theory indicates that the bow wave was crossed twice during a 3-hr interval following the time of closest approach of Mariner 4 to Mars, instead of being missed slightly by the spacecraft as indicated in our previous paper in which the theory of this interaction was presented, and the solar wind was considered, for simplicity, to flow along the Sun-Mars line. It is shown that the observed magnetic field changed abruptly at virtually the precise times of the shock crossings indicated by the theory. Although malfunction of the plasma probe prevents observational confirmation of these as shock crossings, this coincidence supports the recent suggestion of the magnetometer experimenters that a bow wave may have been traversed. It also supports the interpretation that the bow wave results from interaction of the solar wind with the ionosphere, and not with a weak planetary magnetic field.

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1. INTRODUCTION

In a recent paper (Spreiter, Summers, and Rizzi, 1970), a theory was presented for the interaction of the solar wind and a nonmagnetic planet that has a sufficient ionosphere to deflect the solar plasma around the planet and its atmosphere; and comparisons of the results were made with the observations of the Mariner spacecraft in their fly-bys of Venus and Mars. The purpose of this brief report is to update the comparisons with the data from the encounter of Mariner 4 with Mars so as to take into account details of the observations that were not known to us when that paper was written.

2. RESUMÉ OF PREVIOUS COMPARISON AND DISCUSSION

In the original comparison, the plot shown in Fig. 1 was presented to show the trajectory of Mariner 4 near Mars (Van Allen et al., 1965), together with the calculated positions for the bow wave for $M_\infty = 8$, $\gamma = 5/3$, and two different shapes for the ionopause, the bounding surface corresponding to the Earth's magnetopause that separates the flowing solar plasma from the ionosphere. The location of the latter was calculated for two different values for H/r_0 , the ratio of the scale height $H = kT/mg$ of the upper ionosphere to the distance r_0 from the center of the planet to the nose of the ionopause. This distance was taken to be 5 percent greater than the 3.4×10^8 cm radius of Mars on the basis of theoretical considerations and electron density profiles for the Martian ionosphere determined from the Mariner 4, 6, and 7 observations. The smaller value for H/r_0 corresponds to the observational data for conditions near the location of the peak electron

density where the mean molecular mass m is dominated by heavy molecules, such as carbon dioxide. The larger value, $H/r_O = 0.25$, is representative of conditions that would prevail if the dominant molecule were atomic hydrogen at a temperature T of about 200°K as is indicated by Kliore et al., (1965) and Fjeldbo and Eshleman (1968) to be the case in the upper ionosphere, the region of greatest importance to the interaction with the solar wind. The associated bow waves are for $M_\infty = 8$, but results of similar calculations for the Earth's bow wave have shown that they would be in virtually the same locations for higher Mach numbers. Significantly lower Mach numbers would lead to more remote locations for the bow wave, but are considered to be unlikely for Mars in view of extensive knowledge of solar wind properties in the vicinity of the Earth's orbit and the prediction of solar wind theory that M_∞ increases monotonically with increasing distance from the Sun.

The conclusion reached in the original presentation of this plot was merely that of consistency between the theoretical indication that the bow wave was not traversed, and the lack of effects attributable to the presence of Mars in the experimenters' accounts of the data from the magnetometer (Smith et al., 1965), the plasma probe (Lazarus et al., 1967), and the energetic particle detectors (Van Allen et al., 1965 and O'Gallagher and Simpson, 1965). Moreover, the closest approach of Mariner 4 to the calculated bow wave was made during the portion of the trajectory indicated by the dashed line when occultation by Mars prevented reception on Earth of data from the spacecraft.

3. OBSERVATIONAL AND THEORETICAL EVIDENCE FOR MARTIAN BOW WAVE ARISING FROM INTERACTION OF THE SOLAR WIND AND THE IONOSPHERE

More recently, however, it has been reported by Smith (1969) and Kavanagh et al., (1970) that a closer examination of the magnetometer data indicates that Mariner 4 may have detected a Martian bow wave, although its effects are weak and its presence could not be confirmed by the other instruments. In Fig. 2 are reproduced 16 hr of the Mariner 4 magnetometer record (Smith, 1969) showing the intensity $|B|$ of the field as the spacecraft passed Mars. This quantity is plotted as a function of the time that the data was received at Earth, and is 12 min later than the time at which the measurements were made and transmitted by the spacecraft. The distance of the spacecraft from the center of Mars is indicated by the aerocentric distance scale at the top of the plots. The point of closest approach to Mars is denoted by CA. The two abrupt changes in $|B|$ signify crossings of the proposed Martian bow wave. Those authors see fit, however, to repeat the cautioning of the experimenters (Smith et al., 1965 and Smith, 1969) that the field disturbances seen while the spacecraft was near Mars could have been interplanetary field fluctuations bearing no relation to the planet. Although data from the plasma detector reported by Lazarus (1967) show a slightly broader than average energy spectrum from about 300 to 100 eV when the spacecraft was inside the proposed bow wave, these indications were considered indecisive for the confirmation of the shock wave's presence because failure of the instrument's high voltage supply made the lower energy data unreliable. If, however, it is

assumed that the magnetic discontinuities do, in fact, signify crossings of the bow wave, the locations of the crossings can be interpreted (Dryer and Heckman, 1967) as indicating the existence of a Martian magnetic field having a dipole moment about 2.1×10^{-4} that of the Earth.

The alternative interpretation that the Martian bow wave results from the presence of an ionosphere, and may develop even in the absence of a planetary field, gains substantial support from the remainder of the results shown in Fig. 2. These consist of a plot of the trajectory of Mariner 4 superposed on a plot of the bow wave and ionopause for $M_\infty = 8$, $\gamma = 5/3$, and $H/r_0 = 0.25$. The latter are identical to the results of Fig. 1 for the same conditions except that (a) the direction of the solar wind has been rotated 4.5° from the Sun-Mars line to allow for the aberration effects of the motion of Mars about the Sun, in the same way as done previously by Smith (1969) in a similar-appearing plot made using a scaled-down drawing of the Earth's bow wave and magnetopause, and (b) the calculated shock wave location has been indicated for greater distances downstream of the planet. To facilitate comparison with the magnetometer record, markers have been added to the trajectory to indicate the time at which measurements at each point were received at Earth. The times at which the trajectory crossed the calculated bow wave are indicated on the magnetometer record by the vertical dashed lines labeled shock. Their near-perfect coincidence with the times of abrupt changes in $|B|$ supports the proposition that these data do indeed provide the signature of a Martian bow wave and, since Mars almost certainly possesses an ionosphere having a ratio H/r_0 of the order of

.25 in its upper levels, that its existence arises from the interaction between the solar wind and the planetary ionosphere along the lines described by Spreiter, Summers, and Rizzi (1970).

A corollary is that there is no need to postulate a planetary magnetic field to account for the observations. The value proposed by Dryer and Heckman (1967) may still be regarded as an upper limit for the strength of a dipole field, but the actual existence of such a Martian field should not be inferred from the Mariner 4 observations.

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FIGURE TITLES

- Fig. 1. Trajectory of Mariner 4 past Mars, projected into a plane by rotation about the Sun-Mars line, and calculated locations of the ionopause and bow wave for $M_\infty = 8$, $\gamma = 5/3$, and $H/r_0 = 0.01$ and 0.25 (Spreiter, Summers, and Rizzi, 1970). The solar wind direction is considered to be along the Sun-Mars line.
- Fig. 2. Trajectory of Mariner 4 past Mars, projected into a plane by rotation about the Sun-Mars line; calculated location of the ionopause and bow wave for $M_\infty = 8$, $\gamma = 5/3$, and $H/r_0 = 0.25$ (Spreiter, Summers, and Rizzi, 1970) rotated 4.5° to allow for aberration effects arising from Mars' orbital motion as viewed along the trajectory of Mariner 4 (Smith, 1969); and magnetic record from the latter source showing abrupt changes at virtually the precise times that Mariner 4 crossed the calculated position of the bow wave.

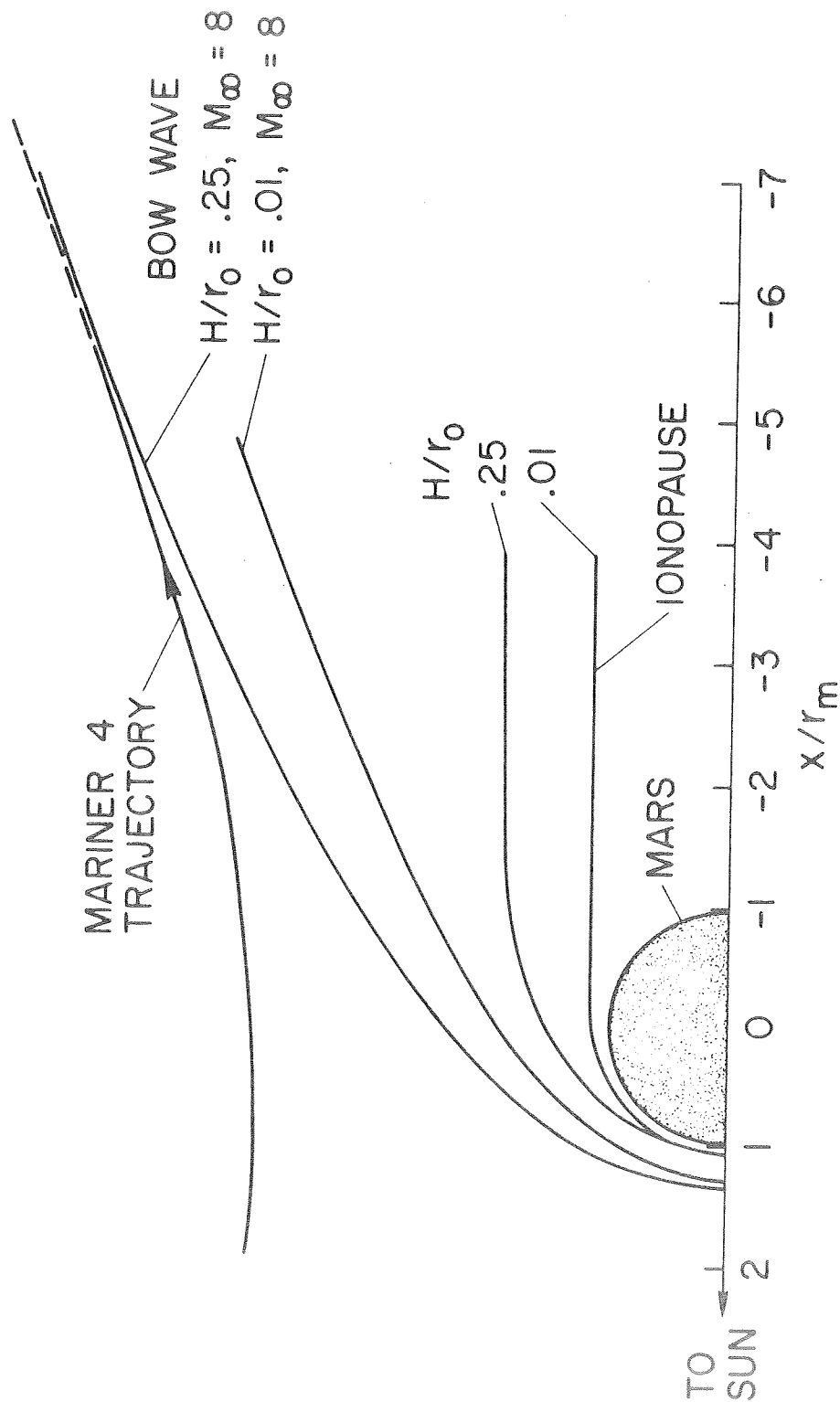


Fig. 1

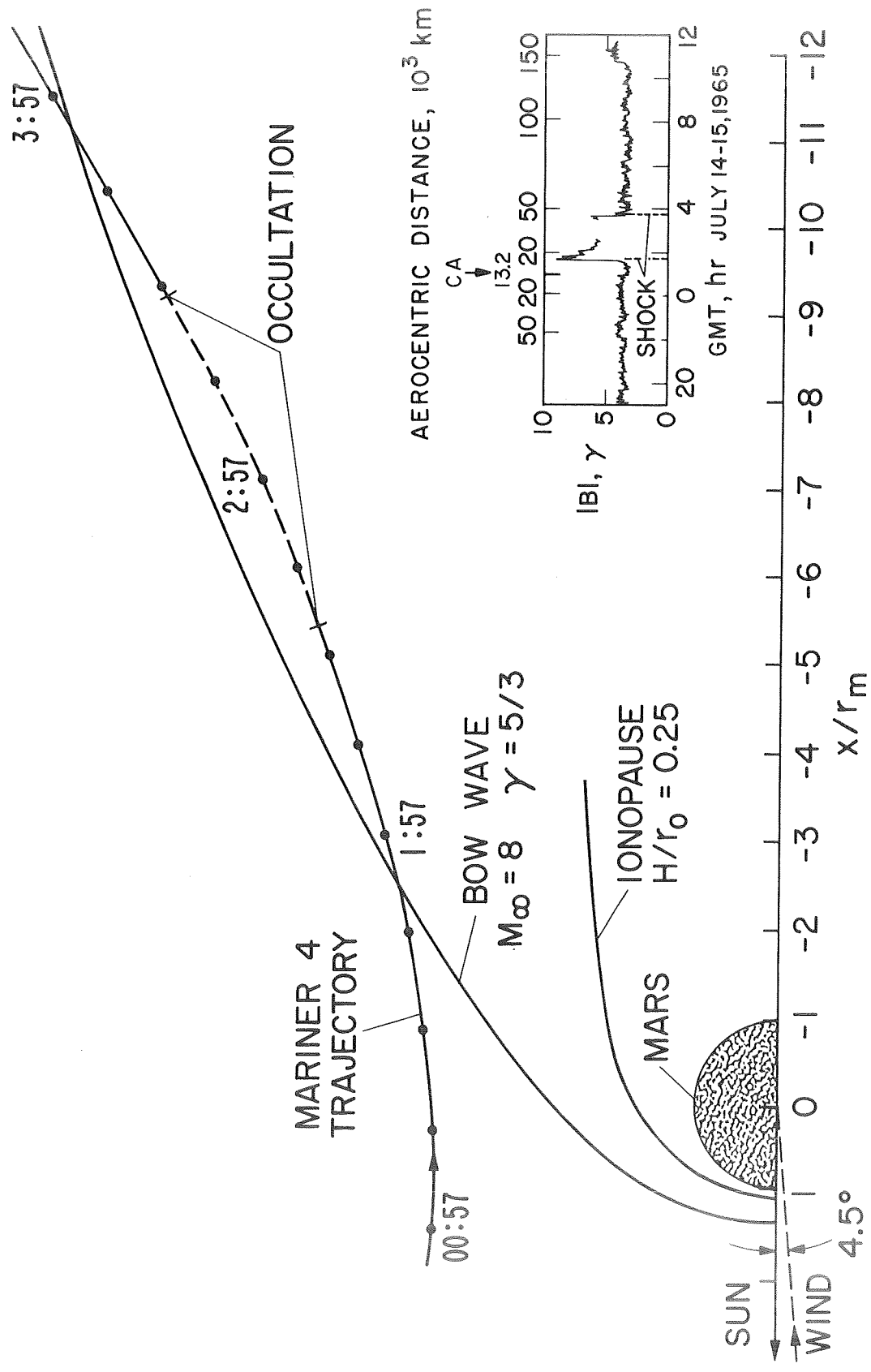


Fig. 2